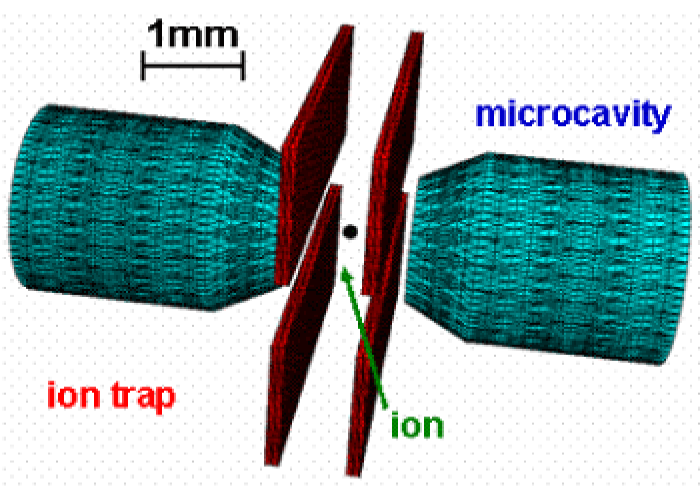
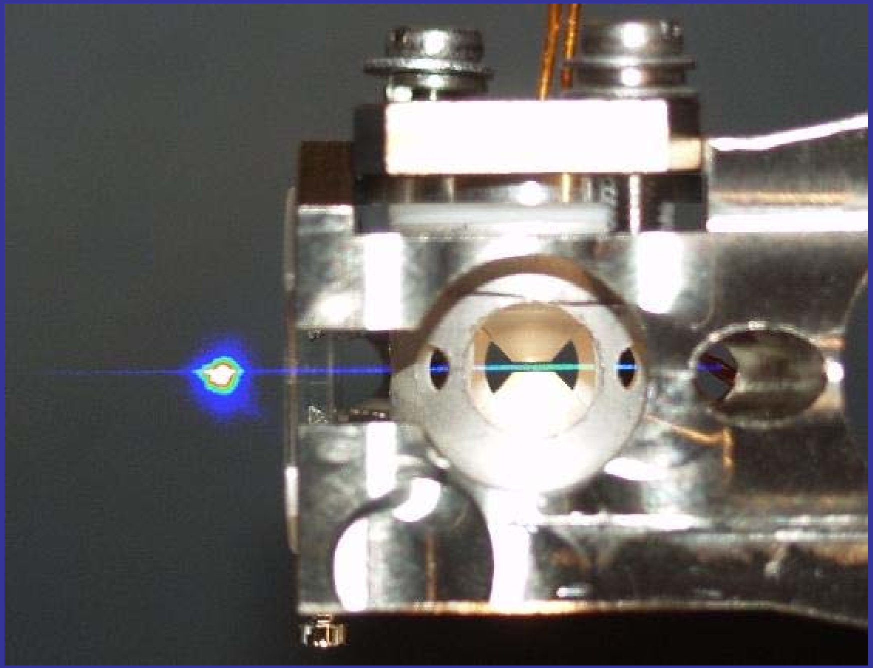
Cavity QED

http://www.quantumoptics.ethz.ch/



http://www2.nict.go.jp/



http://www.wmi.badw.de/SFB631/tps/dipoletrap_and_cavity.jpg

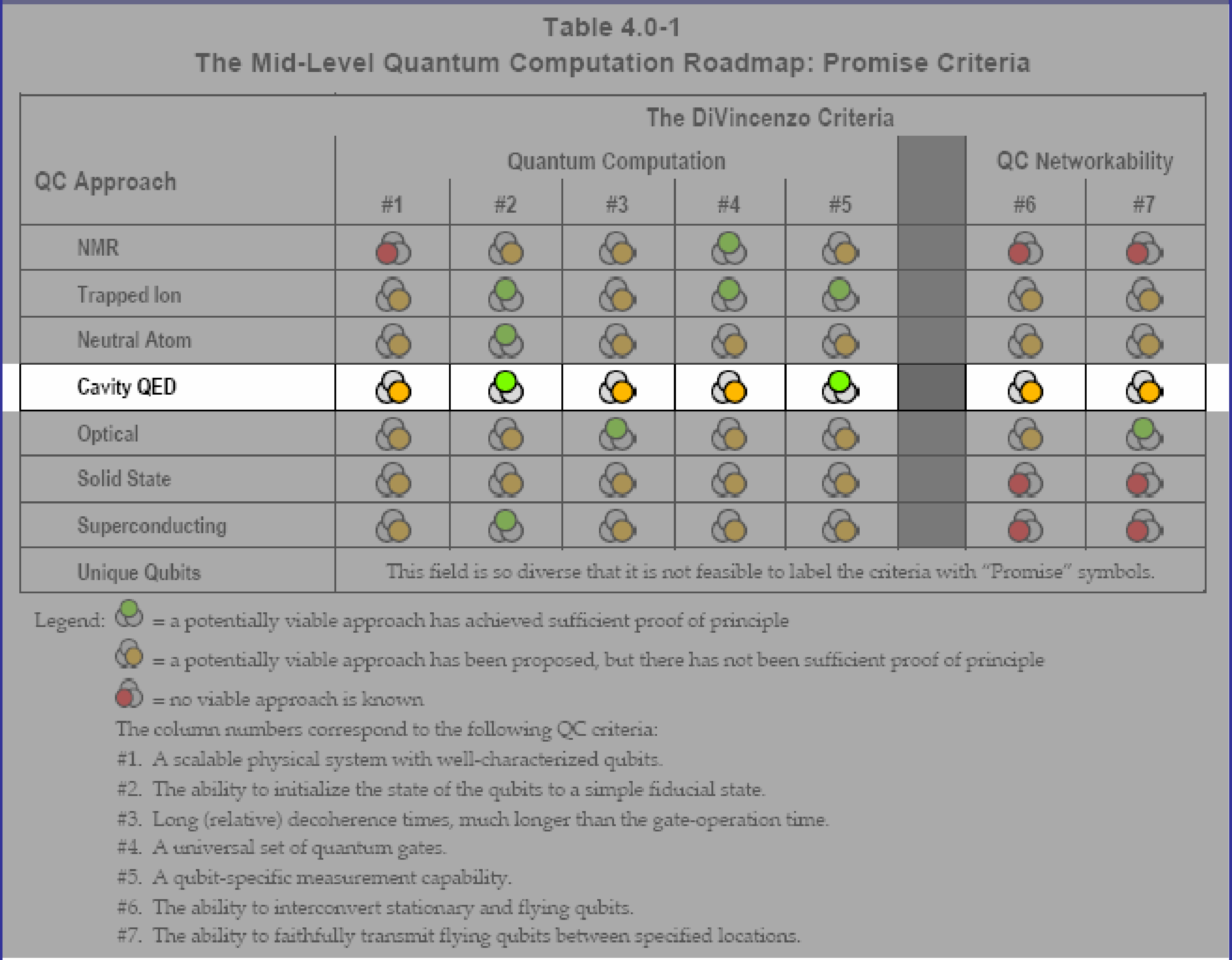


Table 4.0-1
The Mid-Level Quantum Computation Roadmap: Promise Criteria

QC Approach	The DiVincenzo Criteria						
	Quantum Computation					QC Networkability	
	#1	#2	#3	#4	#5	#6	#7
NMR	🔴	🟡	🟡	🟢	🟡	🔴	🔴
Trapped Ion	🟡	🟢	🟡	🟢	🟢	🟡	🟡
Neutral Atom	🟡	🟢	🟡	🟡	🟡	🟡	🟡
Cavity QED	🟡	🟢	🟡	🟡	🟢	🟡	🟡
Optical	🟡	🟡	🟢	🟡	🟡	🟡	🟢
Solid State	🟡	🟡	🟡	🟡	🟡	🔴	🔴
Superconducting	🟡	🟢	🟡	🟡	🟡	🔴	🔴
Unique Qubits	This field is so diverse that it is not feasible to label the criteria with "Promise" symbols.						

Legend: 🟢 = a potentially viable approach has achieved sufficient proof of principle

🟡 = a potentially viable approach has been proposed, but there has not been sufficient proof of principle

🔴 = no viable approach is known

The column numbers correspond to the following QC criteria:

#1. A scalable physical system with well-characterized qubits.

#2. The ability to initialize the state of the qubits to a simple fiducial state.

#3. Long (relative) decoherence times, much longer than the gate-operation time.

#4. A universal set of quantum gates.

#5. A qubit-specific measurement capability.

#6. The ability to interconvert stationary and flying qubits.

#7. The ability to faithfully transmit flying qubits between specified locations.

http://qist.lanl.gov/qcomp_map.shtml

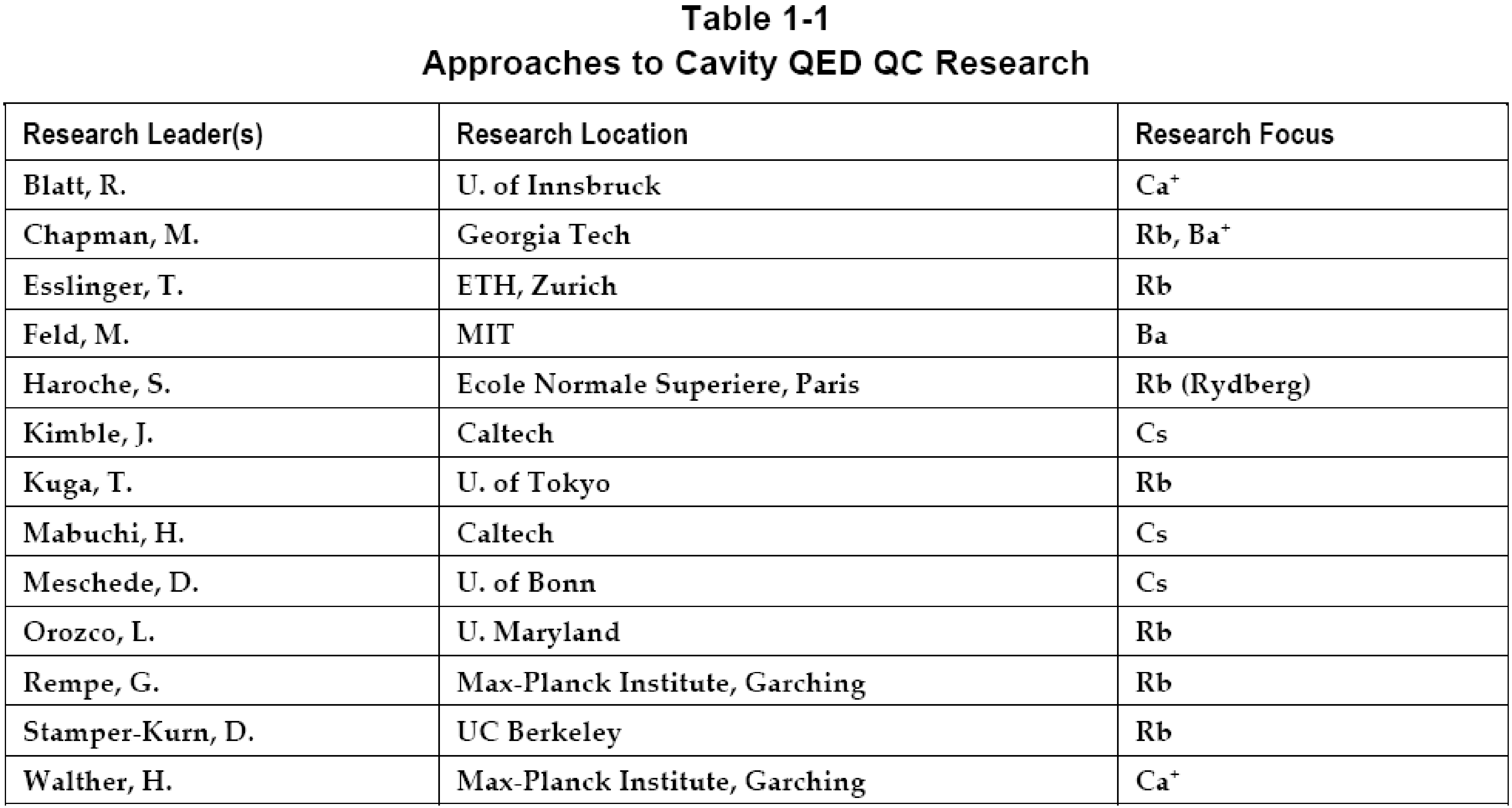
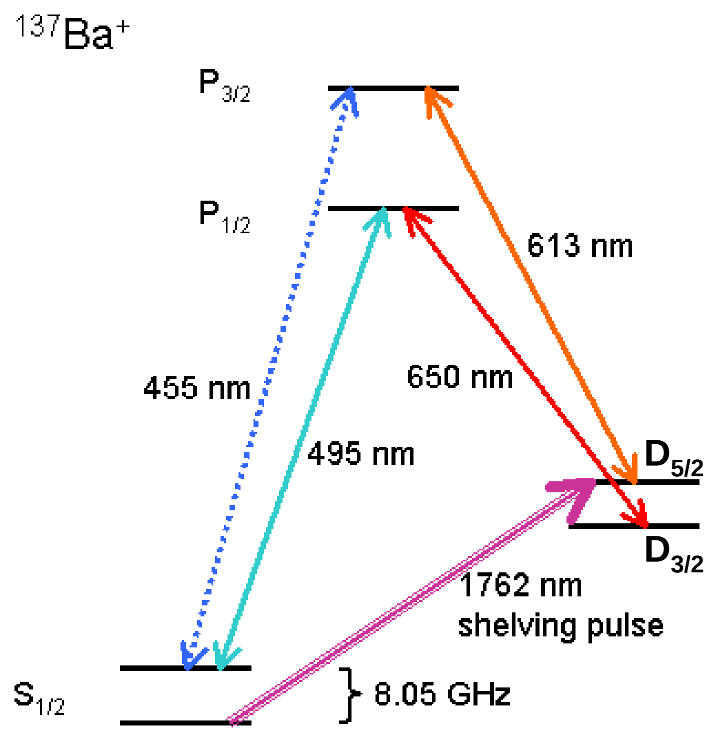


Table 1-1
Approaches to Cavity QED QC Research

Research Leader(s)	Research Location	Research Focus
Blatt, R.	U. of Innsbruck	Ca$^+$
Chapman, M.	Georgia Tech	Rb, Ba$^+$
Esslinger, T.	ETH, Zurich	Rb
Feld, M.	MIT	Ba
Haroche, S.	Ecole Normale Superiere, Paris	Rb (Rydberg)
Kimble, J.	Caltech	Cs
Kuga, T.	U. of Tokyo	Rb
Mabuchi, H.	Caltech	Cs
Meschede, D.	U. of Bonn	Cs
Orozco, L.	U. Maryland	Rb
Rempe, G.	Max-Planck Institute, Garching	Rb
Stamper-Kurn, D.	UC Berkeley	Rb
Walther, H.	Max-Planck Institute, Garching	Ca$^+$

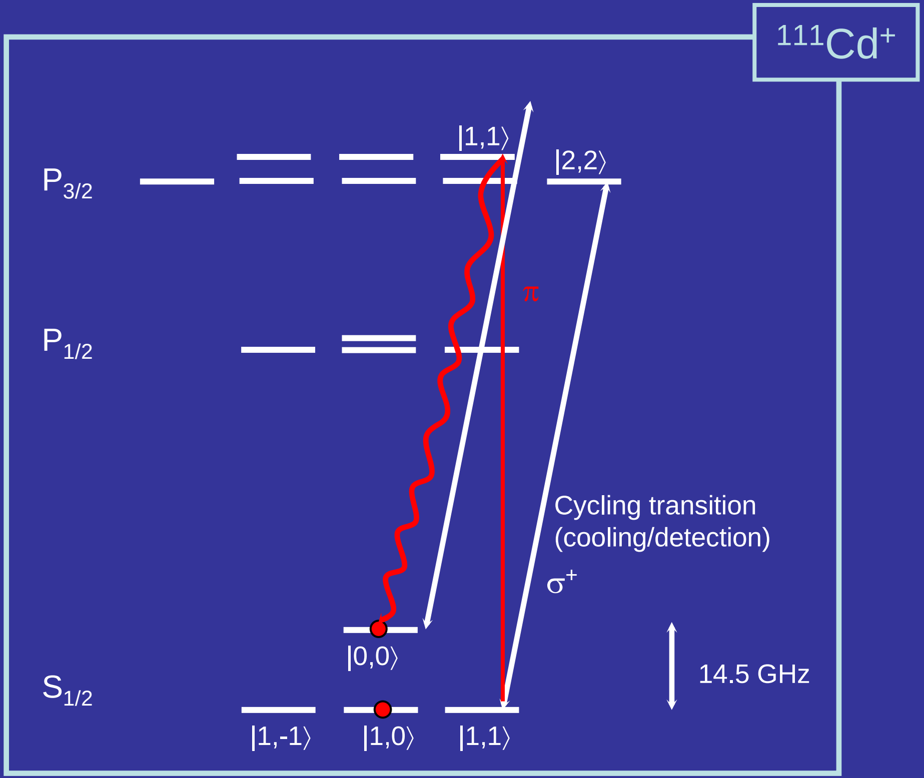
Qubits: single atoms or ions (also, artificial atoms)



- A cavity QED system is usually combined with and atom or ion trap
- Two-level system formed by either the hyperfine splitting of the ground state ("hyperfine" qubit) or by the ground state and a metastable excited state ("optical" qubit)
- The atom can interact with the laser field ("classical" field) and the cavity field ("quantum" field)
- Qubit state preparation and detection techniques are well established and robust

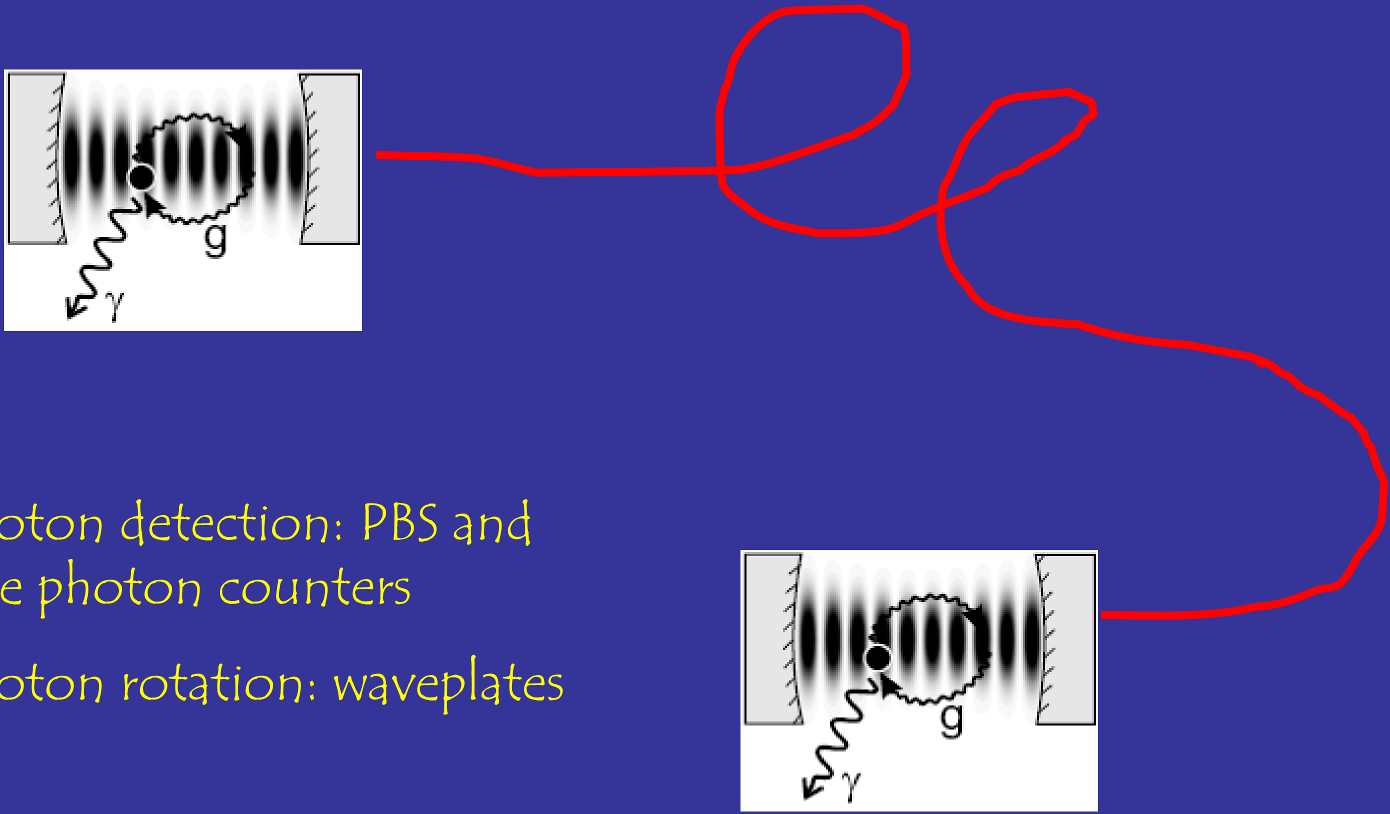
Qubit preparation and detection

- Initialization of the qubits state is via optical pumping: applying a laser light that is decoupled from a single quantum state
- Detection by selectively exciting one of the qubit states into a fast cycling transition and measuring photon rate. May also start by "shelving" one of the qubit states to a metastable excited state, then applying resonant laser light. The qubit state that ends up scattering laser light appears as "bright", while the other state appears as "dark".
- Both the preparation and the detection steps have been demonstrated to work with over 99% efficiency with trapped ions.



Other qubits: photons

- Cavity QED quantum computing makes use of photons to both mediate the atomic qubit entanglement and to transfer quantum information over long distances.



- Photon detection: PBS and single photon counters
- Photon rotation: waveplates

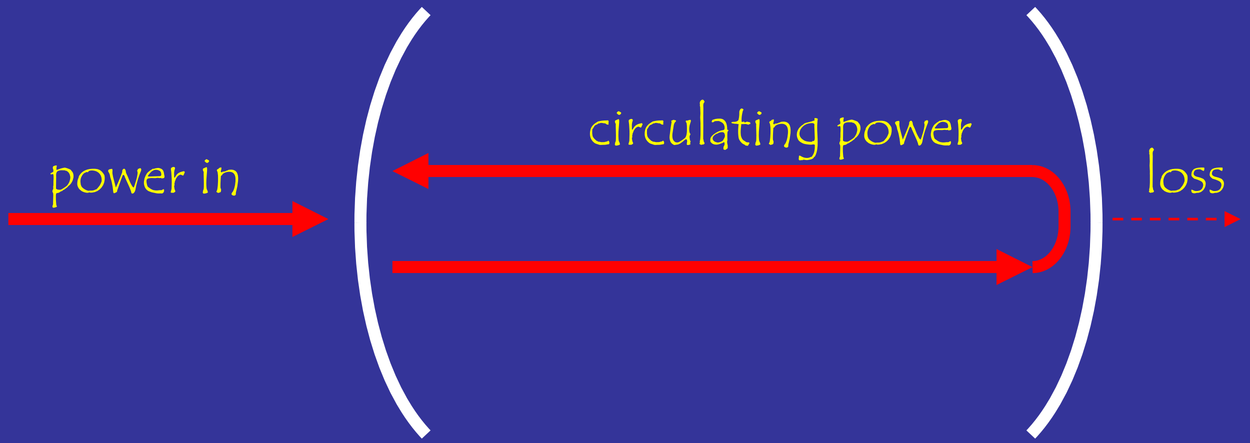
Cavity Quantum ElectroDynamics

◇ In cavity QED we want to achieve conditions where single photon interacts so strongly with an atom that it causes the atom to change its quantum state.

◇ This requires concentrating the electric field of the photon to a very small volume and being able to hold on to that photon for an extended period of time.

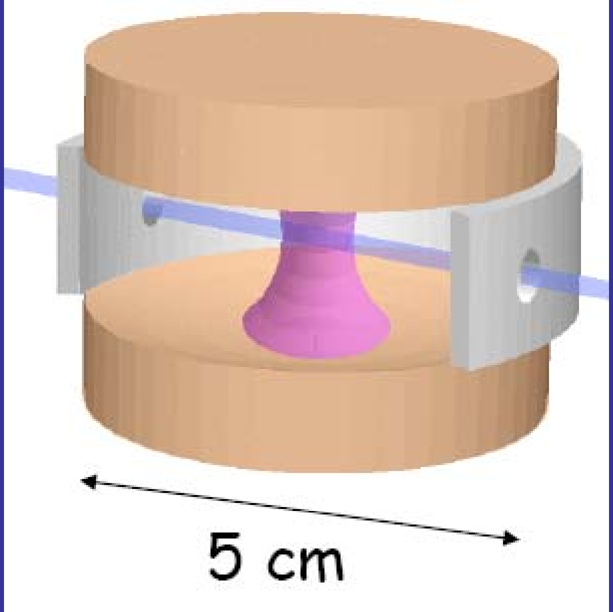
◇ Both requirements are achieved by confining photons into a small, high-finesse resonator.

$F = 2\sqrt{R}/(1 - R)$, where R is mirror reflectivity



Microwave resonators

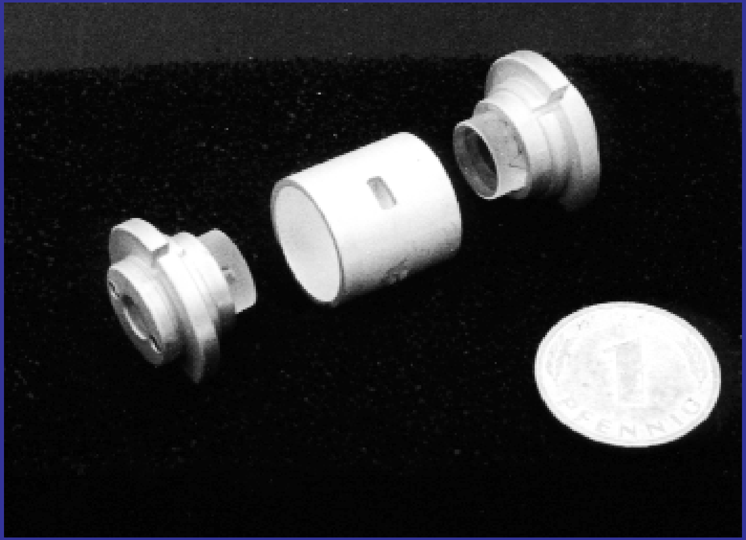
- Microwave photons can be confined in a cavity made of good metal. Main source of photon loss (other than dirt) is electrical resistance.
- Better yet, use superconductors! Cavity quality factors (~ the finesse) reach ~ few × 10^8 for microwave photons at several to several tens of GHz.
- Microwave cavities can be used to couple to highly-excited atoms in Rydberg states. There are proposals to do quantum computation with Rydberg state atoms and cavities.



S. Haroche, "Normal Superior School"

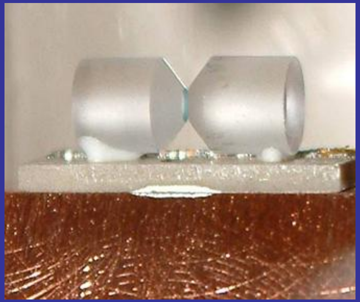
The optical cavity

- The optical cavity is usually a standard Fabry-Perot optical resonator that consists of two very good concave mirrors separated by a small distance.



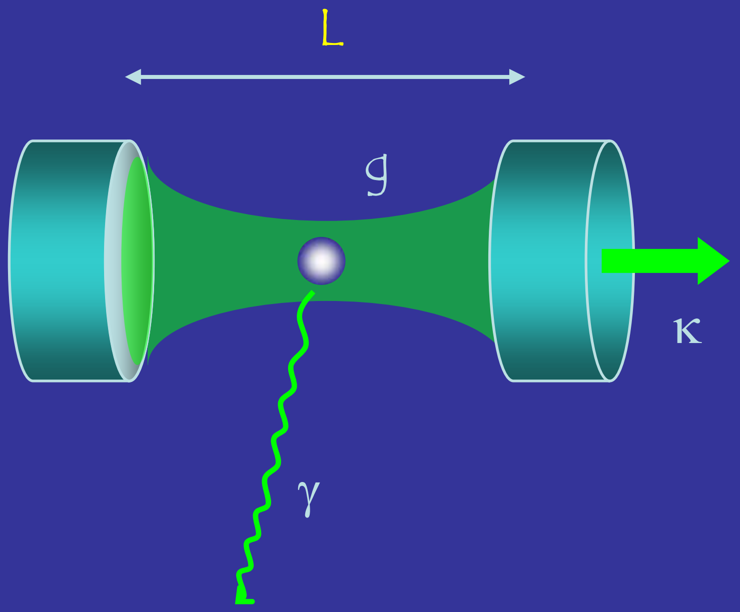
G. Rempe - MPQ

- The length of the cavity is stabilized to have a standing wave of light resonant or hear-resonant with the atomic transition of interest.
- Making a good cavity is part black magic, part sweat and blood...
- These cavities need to be phenomenally good to get into a regime where single photons trapped inside interact strongly with the atoms.



M. Chapman - GATech

Strong coupling regime



Strong coupling:

$$\frac{g^2}{\kappa\,\gamma} >> 1$$

- Atom-cavity coupling:

$$g = \frac{1}{2\cdot\pi}\cdot\sqrt{\frac{6\cdot\lambda\cdot\gamma\cdot c}{\sqrt{2\cdot r\cdot L^3 - L^4}}}$$

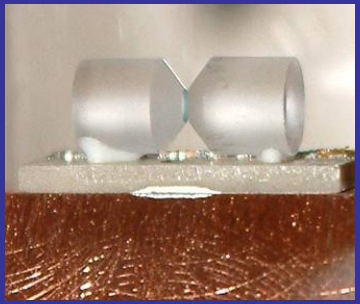
λ is the wavelength
r is the mirror curvature radius

- Cavity decay rate:

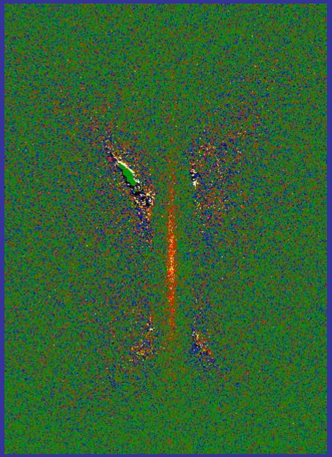
$$\kappa = \frac{\pi\cdot c}{L\cdot F}\cdot\frac{1}{2\cdot\pi}$$

F is cavity finesse

The technology: mirrors



M. Chapman - GATech



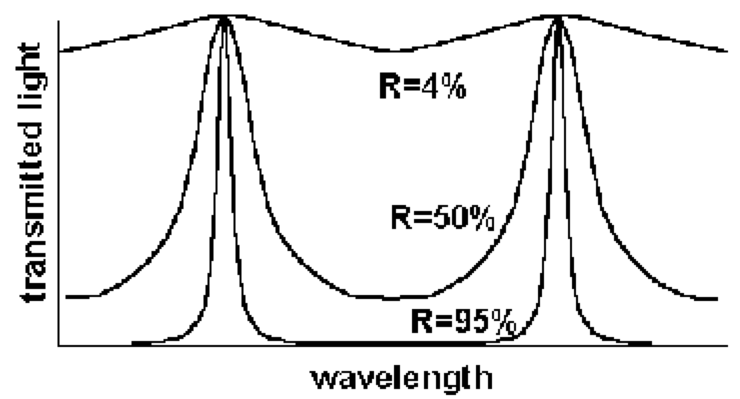
- To make $g \gg \kappa$ we need:
  - a small-volume cavity to increase g
  - a very high-finesse cavity to reduce κ
  - "clean" cavity to reduce other losses

- Strong-coupling cavities use super-polished mirrors (surface roughness less order of 1 Å, flatness $\lambda/100$) to reduce losses due to scattering at the surface.

- Mirrors have highly-reflective multi-layer dielectric coatings (reflectivity at central wavelength better than 0.999995, meaning finesse higher than 500000).

- Mirrors have radius of curvature of 1 – 5 cm, and small diameter. Mirror spacing is 100 micron down to 30 micron. These features of the cavities make for stronger confinement of photons for higher g.

The technology: cavity stabilization

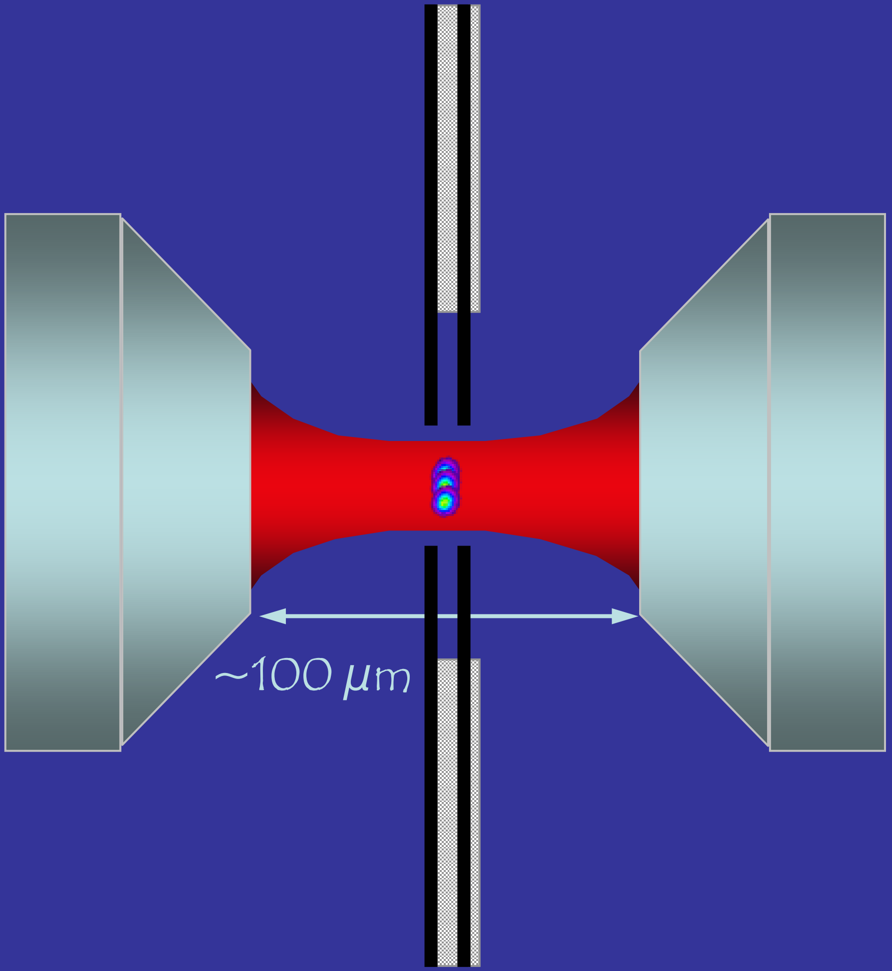


Good cavities have very narrow resonant lines. Thus, to make sure there is a standing wave in the cavity, its length has to be kept fixed to a very high precision.

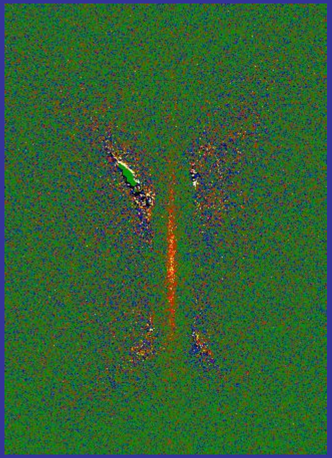
A 100 micron long cavity has to be to about 10^{-15} m, or about the size of the atomic nucleus!

Takes rooms full of electronics dedicated to cavity lock.

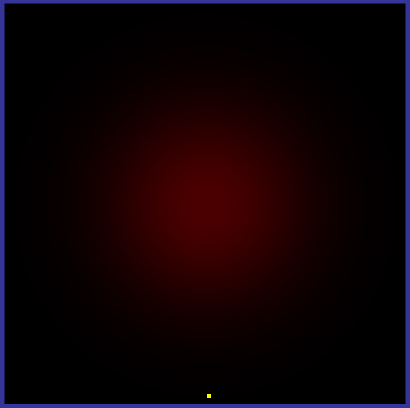
Combining atom trapping and cavity



Thin ion trap inside a cavity (Monroe/Chapman, Blatt)

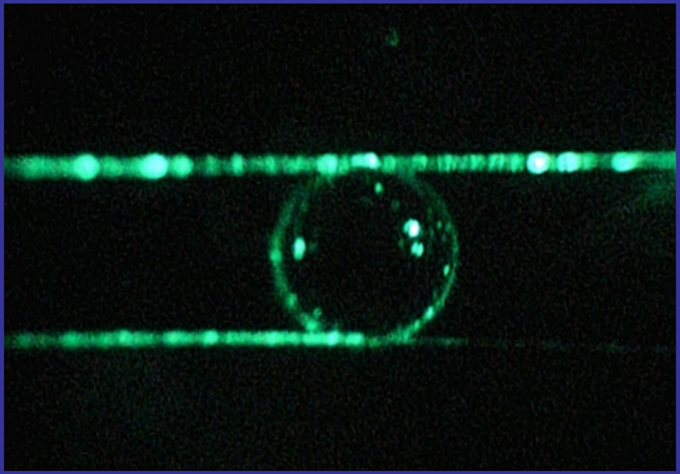


Optical lattice confining atoms inside a cavity (M. Chapman)



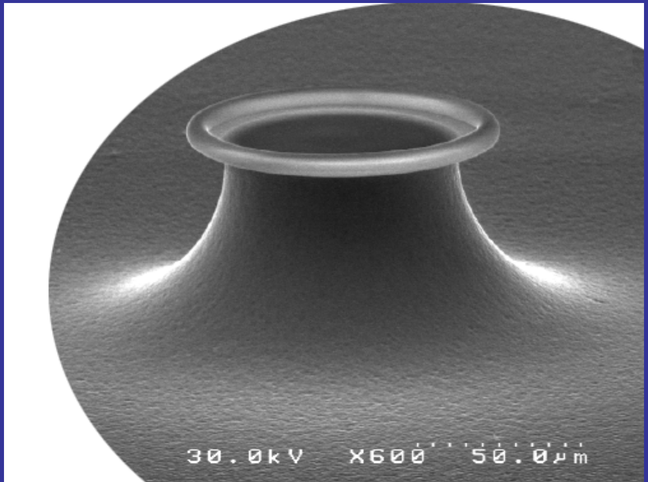
Cavity field used to trap atoms (G. Rempe)

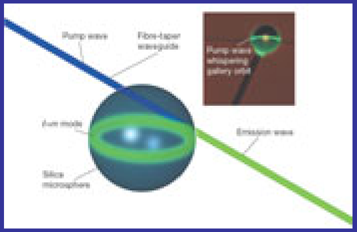
Other cavities: whispering gallery resonators



Whispering cavity resonator laser
(http://physics.okstate.edu/shopova/research.html)

J. Kimble (Caltech)





- Quality factors of 10^8 and greater
- Simple (sort-of) technology – just make a nice, smooth glass sphere ~50 micron in diameter…
- Evanescent field extends only a fraction of the wavelength (i.e. ~100 nm) outside the sphere – need to place atoms close to the surface.
- "Artificial atoms" such as quantum dots can be used…

Challenges of cavity QED QC

- Cavity QED quantum computing attempts to combine two very hard experimental techniques: the high-finesse optical cavity and the single ion/atom trapping. This is not just doubly-very-hard, but may well be (very-hard)^2

- Assuming "hard" › 1, we have "very hard" » 1,
  and ("very hard")^2 » "very hard"

- However, the benefits of cavity QED, namely, the connection of static qubits to flying qubits, are very exciting and are well worth working had for.